How Can Strange Quark Matter Occur Deeply in the Atmosphere?

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Abstract

Motivated by some recent cosmic ray experiments we study the properties of strange quark matter near flavour equilibrium. Using Fermi-gas model we argue that, contrary to some claims, the geometrical radii of quark matter strangelets are not smaller but rather comparable to those of ordinary nuclei. We propose therefore a scenario of propagation of strangelets through the atmosphere which still allows for their deep penetration.

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In astrophysical literature one finds a number of phenomena that are both puzzling and extremaly unusual or unique. They are interested because they apparently do not belong to any known classes of registered events. Some of them are regarded as a manifestation of the so called *strange matter*. In particular it concerns such events as: anomalous cosmic ray bursts from *Cygnus* $X-3$ [1]; extraordinary high luminosity gamma-ray bursts from the supernova remnant $N49$ in the Large Magellanic Cloud [2]; the so called *Centauro* events [3] (characterised by anomalous composition of secondary particles with almost no neutral pions present). In this last case, if it would really be caused by some kind of *strange quark matter* (SQM) called *strangelets*, their observation at the atmospheric depth as large as ~ 500 g/cm^2 would require unusual penetrability of these lumps of SQM [4] (i.e., their geometrical sizes or interaction cross sections should be much smaller than the typical nuclear size).

Typical SQM consists of roughly equal number of up, down and strange quarks and it has been found to be the true ground state of QCD [5, 6, 7][1]. However, any SQM produced at very early stage of the history of Universe would have evaporated long time ago [8]. On the

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[1]It is therefore absolutely stable at high mass numbers A and because the energy per baryon in SQM could be smaller than that in ordinary nuclear matter, it would be more stable than the most tightly bound ^{56}Fe nucleus.

other hand, there are places where the SQM may still exists at present [5, 8]. It is probably continously produced in neutron stars with a superdense quark surface and in quarks stars with a thin nucleon envelope [9] and collisions of such objects could produce small lumps of SQM, strangelets with $10^2 < A < 10^6$, permeating the Galaxy and possibly reaching also the Earth (i.e., *a priori* being detectable here).

There are several reports suggesting direct candidates for SQM. In particular, anomalous massive particles, which can be interpreted as strangelets, have been apparently observed in three independent cosmic ray (CR) experiments:

(*i*) In counter experiment devoted to study primary CR nuclei two anomalous events have been observed [10]. They are consistent with values of charge $Z \simeq 14$ and of atomic numbers $A \simeq 350$ and $\simeq 450$ and cannot be accounted for by the conventional background. Such values of Z and A are fully consistent with the theoretical estimation for ratio Z/A in SQM [11].

(*ii*) The so called Price's event [12] with $Z \simeq 46$ and $A > 1000$, regarded previously as possible candidate for magnetic monopole, turned out to be fully consistent with the above ratio Z/A for SQM [13].

(*iii*) The so called Exotic Track with $Z \simeq 20$ and $A \simeq 460$ has been reported in [14]. The name comes from the fact that although it was observed in emulsion chamber exposed to CR on balloon at the atmospheric depth of only 11.7 g/cm^2 its arrival zenith angle of 87.4 deg means that the projectile causing that event traversed ~ 200 g/cm^2 of atmosphere (in contract to events (*i*) and (*ii*) where the corresponding depths were of the order of $5-15$ g/cm^2 of atmosphere only).

The Exotic Track event motivated the (balloon born emulsion chamber) JACEE [15] and Concorde aircraft [16] experiments to search for strangelets with such long mean free paths. In fact, authors of [15, 16] suggest that the interaction mean free path for strangelets in atmosphere is of the order of $\lambda_{\rm S} = 124$ g/cm^2 for $A = 100$ decreasing to $\lambda_{\rm S} = 59$ g/cm^2 only for $A = 1000$. These values are surprisingly close to that for protons at comparable energies ($\lambda_{proton} = 60 - 70$ g/cm^2) and are much bigger than that for a normal nucleus ($\lambda_{nucleus} \simeq 3.8$ g/cm^2 for $A = 100$). This means that (according to [15, 16]) strangelets should have geometrical radii much smaller than those of the ordinary nuclei or, correspondingly, much smaller interaction cross sections (this would also agree with the SQM interpretation of Centauro events mentioned before)[2].

In this Letter we would like to show that, contrary to the above expectations, geometrical radii of strangelets are most probably comparable to those of the ordinary nuclei. Nevertheless, we shall also show that it is still possible to expect some strangelets occuring deeply in the atmosphere as advocated by [14, 15, 16].

Let us consider a lump of SQM visualised after [6, 7] as Fermi gas of up, down and strange quarks, with total mass number A and confined in a spherical volume $V \sim A$. Its radius is given

[2] So far the results are negative: no evidence for strangelets with $Z > 26$ that survived passing of ~ 100 g/cm^2 of atmosphere was found [15, 16].

by

$$R = r_0 A^{1/3}, \tag{1}$$

where the rescaled radius r_0 is determined by the number density of the strange matter, $n = A/V$ [7]. This in turn is given by the sum of densities of each quark species under consideration, $n = \frac{1}{3}(n_u + n_d + n_s)$, where

$$n_i = -\frac{\partial \Omega_i}{\partial \mu_i} \tag{2}$$

and thermodynamical potentials $\Omega_i(m_i, \mu_i)$ are related to chemical potentials μ_i. Because chemical potentials of interest here are of the order of $\mu \sim 300$ MeV, one can neglect the (current) masses of up and down quarks and leave only the mass of the strange quark, which we shall denote by m. Taking into account the QCD $\mathcal{O}(\alpha_c)$ corrections to the properties of SQM in calculating the respective thermodynamical potentials $\Omega_i(m_i, \mu_i, \alpha_c)$ (renormalizing them at $m_N/3 = 313$ MeV) [6], the rescaled radius is given by

$$r_0 = \left[\frac{3\pi}{2\left(1 - \frac{2\alpha_c}{\pi}\right)(\mu^3 + m^3)} \right]^{1/3}. \tag{3}$$

In Fig. 1a we show its dependence on the ratio of the strange quark mass to its chemical potential, m/μ for the case of $\alpha_c = 0$ (i.e., ignoring one-gluon exchanges inside the Fermi gas [7]). For the values commonly accepted for SQM (like $m \simeq 150$ MeV and $\mu \simeq 300$ MeV) [5, 6, 7], the values of r_0 of the strangelets are comparable with that for the ordinary nuclear matter (being only a bit smaller with difference not exceeding 10% - 20%). Fig. 1b summarizes the dependence of the r_0 on the QCD coupling constant α_c. It turns out that in this case the chemical equilibrium shifts towards bigger number of strange quarks without, however, significantly influencing the number density. As one can see the QCD corrections lead to the slight increase of r_0 (not exceeding 30%).

Fig. 1 shows therefore that the expected decrease of the radius of strangelet is nowhere as dramatic as it has been estimated in Refs. [15, 16]. It means that the expected geometrical cross sections of SQM are, in fact, not much smaller than those for normal nuclei, in any case not enough to explain alone the occurences of anomalous events detected deeply in the atmosphere. It does not mean, however, that some SQM cannot be registered there and in what follows we shall propose a simple (speculative but plausible) scenario, which can be summarized as follows: strangelets reaching so deeply into atmosphere are formed in many successive interactions with air nuclei of much heavier lumps of SQM entering our atmosphere. Assuming now the simplest possible scenario, namely that after every such collision strangelet of mass number A_0 becomes the new one with $A_0 - A_{air}$ [3], one obtains the resultant mass number of strangelet registered at depth h, $A(h)$, as a function of h as shown in Fig. 2. As one can see, bigger initial strangelets (i.e., with higher mass number A_0) can penetrate much more deeply into atmosphere untill $A(h)$ exceeds critical A_{crit}, after which point they just evaporate by the emission of neutrons.

[3] Notice that incoming strangelet has $A_0 >> A_{air}$ and that it is much more stable than the target air nucleus. For simplicity we tacidly assume here that air nucleus destroys totally the corresponding (equal to it) part of the incoming lump of SQM, our estimation provides therefore a lower limit of what should be expected in more detailed calculations.

Let us now explain our point in more detail. First of all let us note that the practical measure of the stability of strangelet is the so called separation energy dE/dA, i.e., energy, which is required to remove a single baryon from a given strangelet. For example, if $dE/dA > m_N$ strangelet can evaporate (from its surface) neutrons[4]. This energy depends, among other things, on the size of the strangelet, which is usualy given in terms of its mass number A [7]. There exists therefore some critical size given by a critical value of $A = A_{crit}$ such that for $A > A_{crit}$ there will exist some strangelets that are absolutely stable against neutron emission; it depends on the various choices of parameters and vary from $A_{crit} = 300$ to 400 [6, 7]. Suppose now that the energy per baryon in strange matter is $\varepsilon = 919$ MeV [6] and that number densities corresponding to nuclear matter are $n = (110\ \text{MeV})^3$. In such situation for $A \leq 1100$, E/A exceeds already m_N but strangelet does not emit neutrons yet and starts to do so only for $A \leq 320$, at which point dE/dA exceeds m_N [6]. Below this limit strangelet decays rapidly by evaporating neutrons. In view of these remarks it is remarkable that all possible candidates for SQM have mass numbers near or slightly exceeding A_{crit}, namely: $A = 350$ and 450 in [10], $A = 460$ in [14] and $A = 1000$ in [13] and is argued that Centauro event contains probably ~ 200 baryons [4, 3]. Fig. 3 shows atmospheric length traversed after which the strangelet mass number A becomes critical, $A = A_{crit}$, starting from different mass numbers A_0 of the initial strangelets. From it one can read off that strangelets which are observed at depth 200 g/cm^2 should originate from the strangelets of mass number $A_0 = 900$ at the top of the atmosphere whereas Centauro events observed at the mountain altitudes would require original strangelet of $A_0 = 1800$. Unfortunately, the mass distribution of incoming strangelets, $N(A_0)$, is not known. Assuming that strange stars break up in the collisions in a manner resembling the breaking of colliding nuclei (proceeding due to the phase transition close to the critical point), one could expect that the corresponding mass distribution of strangelets should follow a simple power law, like A_0^{γ} [5]. In such a picture power index $\gamma \geq 2$ can accomodate both the observed strangelets and the upper bounds for intensities of those which survived traversing ~ 100 g/cm^2 of atmosphere as provided by [15, 16].

We summarize by stating that most probable the geometrical cross sections of strangelets are not dramatically different from those for the ordinary nuclear matter and cannot therefore explain their apparent very high penetrability through the atmosphere. Instead we propose to interprete such a penetrability of SQM (already discovered or to be yet observed) as indication of the existence of very heavy lumps of SQM entering our atmosphere, which are then decreased in size during their consecutive collisions with air nuclei (i.e., their original mass number A_0 is reduced until $A = A_{crit}$) and finally decay be the evaporation of neutrons.

[4]In principle strangelet is unstable if its energy per nucleon (understood here as 3 quarks), E/A, exceeds the mass of a nuclear system. However, even if $E/A > m_N$ a strangelet would not convert as a whole into nucleons in any finite time because such process would be of extremaly high order in the weak coupling constant.

[5]As a good candidate for its statistical interpretation could serve percolation model of Ref. [17].

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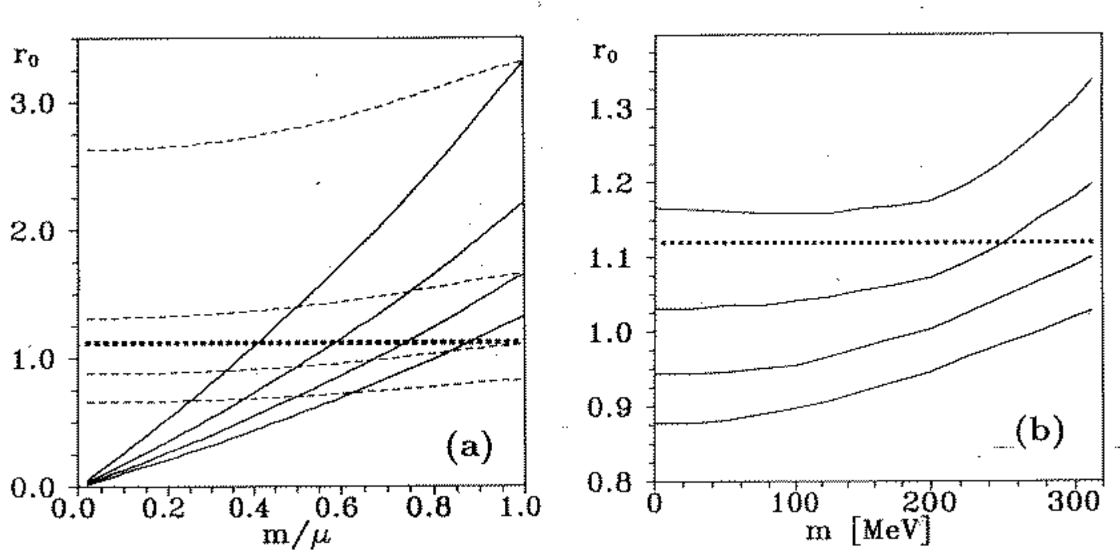

Figure 1: Dependence of the rescaled radius r_0 [fm] (cf. eq.(3): (a) on the ratio of the strange quark mass m to its chemical potential μ, m/μ (solid lines, read from top to bottom, correspond to fixed strange quark masses: $m = 100,\ 150,\ 200,\ 250$ MeV; dashed read from top to bottom correspond to fixed chemical potentials: $\mu = 100,\ 200,\ 300,\ 400$ MeV); (b) on the strange quark mass m for different values of the QCD coupling constant: $\alpha_c = 0.9,\ 0.6,\ 0.3,\ 0.0$ (from top to bottom, respectively). In both cases we show also for reference (by dotted line) the $r_0 = 1.12$ fm corresponding to normal nuclear density $\rho = 0.17$ fm^{-3} $=$ (110 MeV)^3.

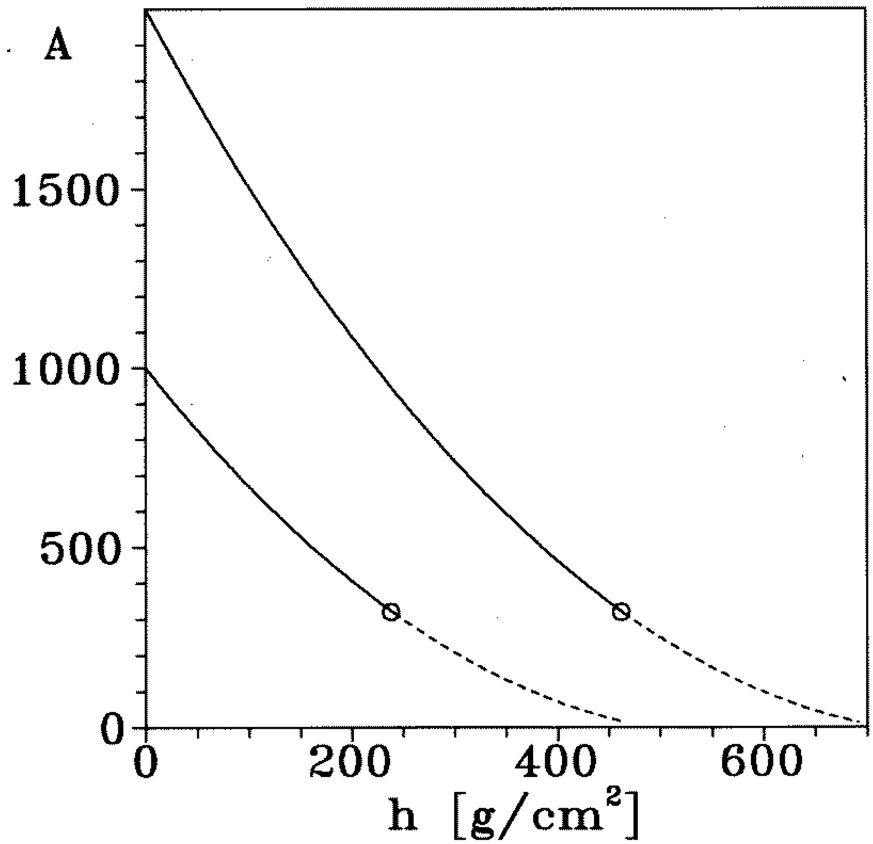

Figure 2: An example of the predicted decrease of the actual size of the strangelet (as given by its mass number A) with depth h of the atmosphere traversed (measured in g/cm^2) for two different initial SQM mass numbers: $A_0 = 1000$ and 2000. Solid lines corrrespond to $A > A_{crit}$ and dashed to $A < A_{crit}$ (in which region strangelets practically dissolve into neutrons).

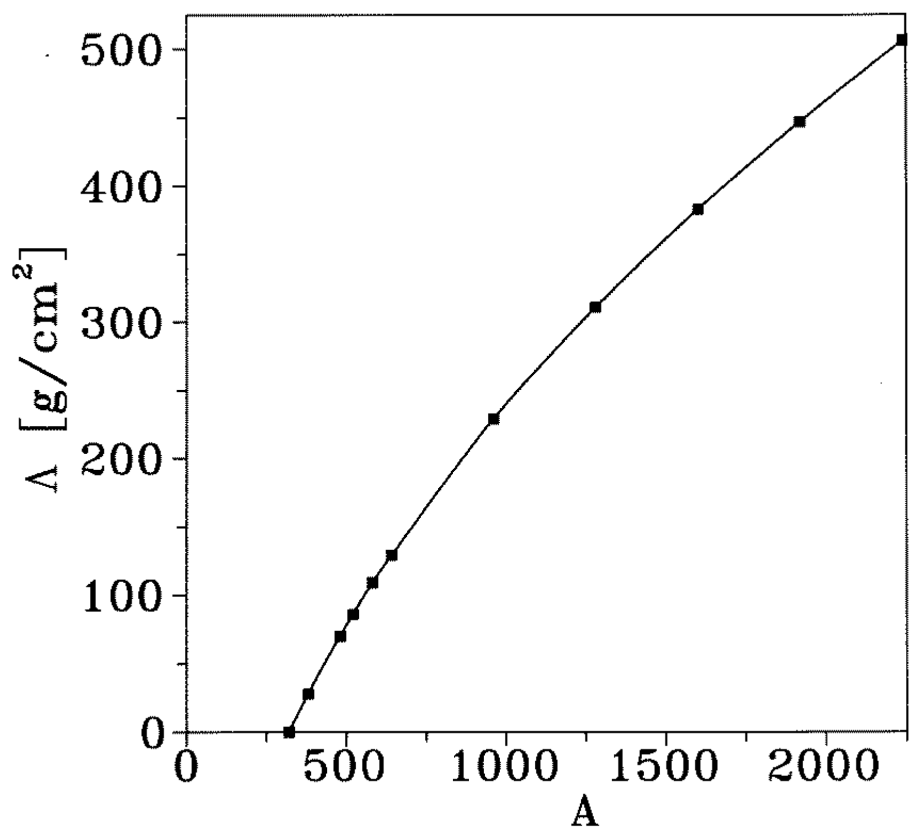

Figure 3: Atmospheric length Λ [g/cm^2] after which initial strangelet reaches its critical dimension, $A = A_{crit}$ drawn as a function of its initial mass number A_0 (here $dE/dA > m_N$ for $A_{crit} \leq 320$). Consecutive full squares indicate (for $A > 600$) points where $A/A_{crit} = 2,\ 3,\ 4,\ 5,\ 6,$ respectively.